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Impact Factor In Thermoacoustic Prime mover Design

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Abstract

Researches for suitable parameters for a project based on "Thermoacoustics" and "Solar Energy" by University of Damascus, software's were developed to be the core for sizing Thermoacoustic devices "Cooler and Prime mover", included the modeling equations of designation. Design strategies were developed. The usage of low technology especially in stack fabrication, as well as to achieve building large sized tunnel that may be used in air conditioning based on solar prime mover is possible. In this paper, parameters of designation were studied to find the impact of affecting temperature gradient over the stack and the desired resonator diameter as a function of temperature gradient and mean pressure when it is prime mover. Some parameters like the heating capacity, and stack spacing were chosen to fit the needs, fabrication, and simplicity requirements. The developed designation resonator diameters were included.

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Keywords: Thermoacoustic, prime mover, stack sizing software, rapid resonater diameter choose.

Nomenclature

ω	*angular frequency*
a	*sound velocity*
K	*Gas thermal conductivity*
ρm	*Gas density*
cp	*Gas heat capacity*
ω	$2\pi f$ *angular frequency*

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μ	*Gas Viscosity*
l	*Half stack plate thickness*
yo	*half plate spacing*
f	*Operating frequency*
A	*Stack cross sectional area*
Π	*Stack perimeter*
$Z()$	*acoustic impedance*
Qc	*cooling power*
Qh	*heating power*
Qcn	*Dimensionless cooling power*
Qhn	*Dimensionless heating power*
D	*Drive ratio*
Po	*Dynamic Pressure,*
Pm	*Average Pressure*
tm	*Average temperature*
δk	*thermal penetration depth*
δv	*viscous penetration depth*
δkn	*Normalized thermal penetration depth*
xs	*Stack center position*
xn	*Normalized center position*
γ	*Ratio of isobaric to isochoric specific heats*
Pr	*Prandtl Number*
ΔTm	*Temperature difference*
ΔTmn	*Normalized Temperature difference*
B	*Blockage ratio or porosity*
Ls	*stack length*
Lsn	*Normalized stack length*
A	*Stack cross sectional area*
Wn	*Dimensionless acoustic power*
W	*Acoustic Power*
$Lt - l$	*the length of the small diameter tube*
k	*Wave number,*
l	*Length of the large diameter tube*
$D1$	*Diameter of large tube*
$D2$	*Diameter of small tube*
Lt	*Total length of resonator*

1. Introduction

A project of building a friendly environmental prime mover based on "Solar Thermoacoustics" for the faculty laboratories in the Faculty of Mechanical and Electrical Engineering in Damascus University is running. The project consists of thermoacoustic experimental devices attached to each other. A modulating driver is driven by a computer which generates an electronic sinuous wave with specific parameters. These waves are amplified then emitted through speakers to create a sound wave which drives the thermoacoustic refrigerator that has no moving part. The prime mover needed to drive this refrigerator is based on solar energy. The heating power needs come through a concentrating dish. The desired dish has a diameter of 100 [cm], which brings out a thermal 100 watt's for concentrated fluid temperature about 350 [C^o]. In this paper impact of temperature gradient value used in sizing a prime mover and resonator diameter will be discussed. With a quick review of modeling equation used in designation model.

Thermoacoustic device can generally be divided into four parts. These parts are known as driver, resonator, stack, and two heat exchangers. The proposed system and the four parts are labeled in Figure (1):

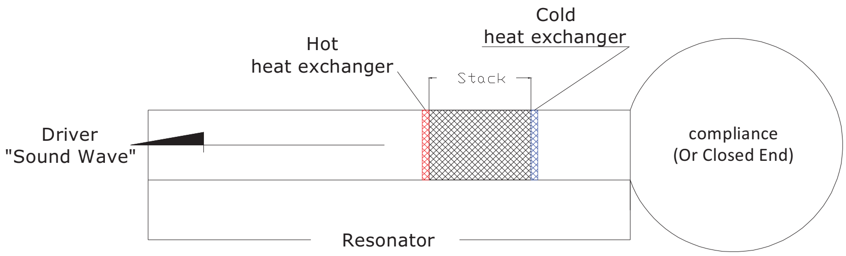

Figure.1: Essential parts of a thermoacoustic driver.

Common thermoacoustic driver parts which are shown in Figure (1). However, there are other models for thermoacoustic drivers, some looks nothing like the model shown above. The driver creates a standing wave in. The wave created by the driver is generally at or near the resonant frequency of the resonator in which the wave oscillates. The stack is located within the resonator and serves in creating more surface area across which the Thermoacoustic effect can take place. Finally, the heat exchangers are used to sink heat from a hot region and reveal the rest of it to the outside. These components are each described individually in details in references. Russel [12] describes a cheap and easy way to build thermoacoustic device. This device is for demonstration purposes only hence it is not very powerful nor efficient. However, it is an excellent starting point for those interested in the field. Actually, Tijani [11] published a paper describing the process used to design a thermoacoustic device from scratch in details. The project we are working on is nearly finished, but the stack required a higher technology which is not available. Alternative solutions were sought, one is bigger spacing.

2. design Strategy

The developed strategy is based on Thermoacoustics strategy modified to fit the specific requirements; and it contains the three essential parts: stack, resonator, heat exchangers, and conducted driver for the prime mover, and the four essential parts for the refrigerator. The strategy is shown in figure (2).

As seen in the design strategies: Δtm is one of the factors to be discussed, the others are mean temperature (tm), mean pressure (pm), parallel sheet thickness (2yo), driving frequency (f), and porosity (B).

3. Working Gas and its thermo physical Properties

The desired gas is Air. However, Hydrogen, Helium, Argon may be discussed same way. Based on the National Institute of Standard and Technology (NIST) Data [9, 24], the polynomial equations which describe thermo physical properties for Air as a function of t_m and p_m, are:

ρ=f1(pm,tm), cp= f2(pm,tm), γ= f3(pm,tm), λ= f4(pm,tm), μ= f5(pm,tm), pr= f6(pm,tm) ,a= f7(pm,tm).

4. Sizing equations used in sizing software

The sizing equations are listed in table (1) for prime mover.

Table (1): Design equations Used in software

element	Design Equations
Resonator	*λ/4-resonator, D2/D1 =0.54,* $l \cong x_s + Ls/2 + 2.x_1$ $Z^{(1)}(l) = \dfrac{p^{(1)}}{A_1.u^{(1)}} = \dfrac{\cot(kl)}{A_1},\ p^{(1)} = p_0^{(1)}\cos(kx),\ u^{(1)} = \dfrac{p_0^{(1)}}{\rho_m.a}\sin(kx)$

	$p^{(2)} = p_0^{(2)} \sin(k(Lt-x))$, $u^{(2)} = \frac{p_0^{(2)}}{\rho_m . a}\cos(k(Lt-x))$, $Z^{(1)}(l) = Z^{(2)}(l)$. $x_1 = \frac{u^{(1)}}{\omega} = \frac{p_o^{(1)}}{\omega\rho_m a}\sin(k x)$, $\cot(k l) = \left(\frac{D1}{D2}\right)^2 \tan(k(L_t - l))$ $(L_t - l) = \frac{\text{atan}\left((D2/D1)^2\cot(k l)\right)}{k}$
STACK	*Prime mover: Mica with, Ks = 0.528 [W/mC]* *yo/δk = 1.1* $\delta_k = \sqrt{\frac{2K}{\rho_m c_p \omega}} \rightarrow \delta_k = \frac{y_0}{1.1} = \sqrt{\frac{2k}{\rho_m Cp 2\pi f}} \rightarrow f = \frac{1.21\, k}{\rho_m Cp\, \pi\, y_o^2}$ $Lsn = -0.2223 * (Cop)^3 + 1.0263 * (Cop)^2 - 1.8811 * (Cop) + 1.4369$ $xn = 0.4485 * (Lsn)^3 - 0.8664 * (Lsn)^2 + 1.1625 * (Lsn) - 0.00705$ $Lsn = Ls.k;\ Xs = xn.k$ $B = \frac{y_0}{y_0 + l}$, $\Gamma = \frac{\nabla Tm}{\nabla Tc} = \frac{\Delta Tmn.\tan(x_n)}{(\gamma-1)B.Lsn}$ $k = \frac{\omega}{a}$, $D = \frac{Po}{Pm}$, $\Lambda = 1 + \sqrt{Pr}.\delta_{kn} + \frac{1}{2}Pr(\delta_{kn})^2$, $\delta_{kn} = \delta_k / y_0 = 0.91$ $Qhn = \frac{\delta_{kn} D^2 \sin(2.x_n)}{8.\gamma.(1+Pr).\Lambda}\left(\Gamma.\frac{1+\sqrt{Pr}+Pr}{1+\sqrt{Pr}} - \left(1+\sqrt{Pr}-\sqrt{Pr}.\delta_{kn}\right)\right)$ $Qn = Q / Pm\, a\, A \rightarrow A = Q / (Qn.Pm.a)$ $W = \frac{1}{4}\Pi\delta_k Ls \frac{\omega.(p_1^o)^2}{\rho_m . a^2(1+\varepsilon_o)\gamma}(\gamma-1)\left(\Gamma.\frac{1}{(1+\sqrt{Pr})\Lambda}-1\right) - \frac{1}{4}\Pi\delta_v Ls\frac{\omega.\rho_m.(\langle u_1^o\rangle)^2}{\Lambda}$ $\frac{d\dot{W}}{dA} = \frac{1}{4}\omega.\delta_k\frac{\lvert p_1\rvert^2}{\rho_m . a^2}(\gamma-1) + \frac{1}{4}\omega.\delta_v.\rho_m.\lvert\langle u_1^o\rangle\rvert^2$ $Wn = -\frac{\delta_{kn} LsnD^2}{4.\gamma}(\gamma-1)B\cos^2(.x_n)\left(\Gamma.\frac{1}{(1+\sqrt{Pr})\Lambda}-1\right) - \frac{\delta_{kn} LsnD^2}{4.\gamma B\Lambda}\sqrt{Pr}\sin^2(.x_n)$ $Wn = W / Pm\, a\, A$
Cold heat exchangers	*optimum length of the cold heat exchanger ~2x1*
Hot heat exchangers	*optimum length of the Hot heat exchanger ~4x1*
Prime mover Acoustic driver	$W_t = W_s - W_{res} - W_{chx} - W_{hhx}$
COP	*COPt =Wt/ Qh*

5. Software

Software was developed in VB9. The software has been written especially for the project as computer aid designation, but it serves all desired designation cases.

6. Results

Increasing "B" will move the desired optimum temperature gradient, and functionality of being refrigerator or prime mover, regarding the mean pressure. "Γ" is the parameter which affects the functionality. As an important result: variable "B" would be a solution for the device to be air conditioner working on summer and winter as seen in figure.

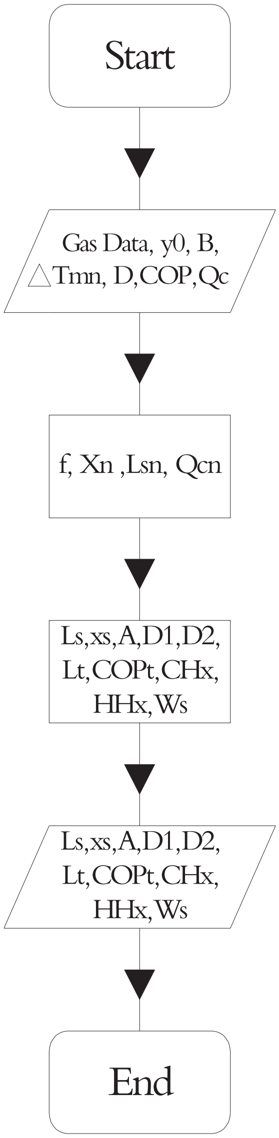

Figure.2: design strategy of a thermoacoustic driver

Actually, for prime movers: increasing "Δtm" increases "COPt". In the other hand, increasing mean pressure increases "COPt" too. The factor may be discussed here is resonator diameter, which affected directly by gas pressure, porosity, and temperature gradient, whereas, temperature gradient has no impact at "COPt" when it becomes higher than 700 [C]. Even when temperature gradient less than 700 [C] but higher than 200 [C], temperature gradient has minimal impact (figure 3). In case of "Δtm =320 [C]", pressure has minimal impact on "COPt" (figure 4). But, it has maximal on "Diameter" (figure 5).

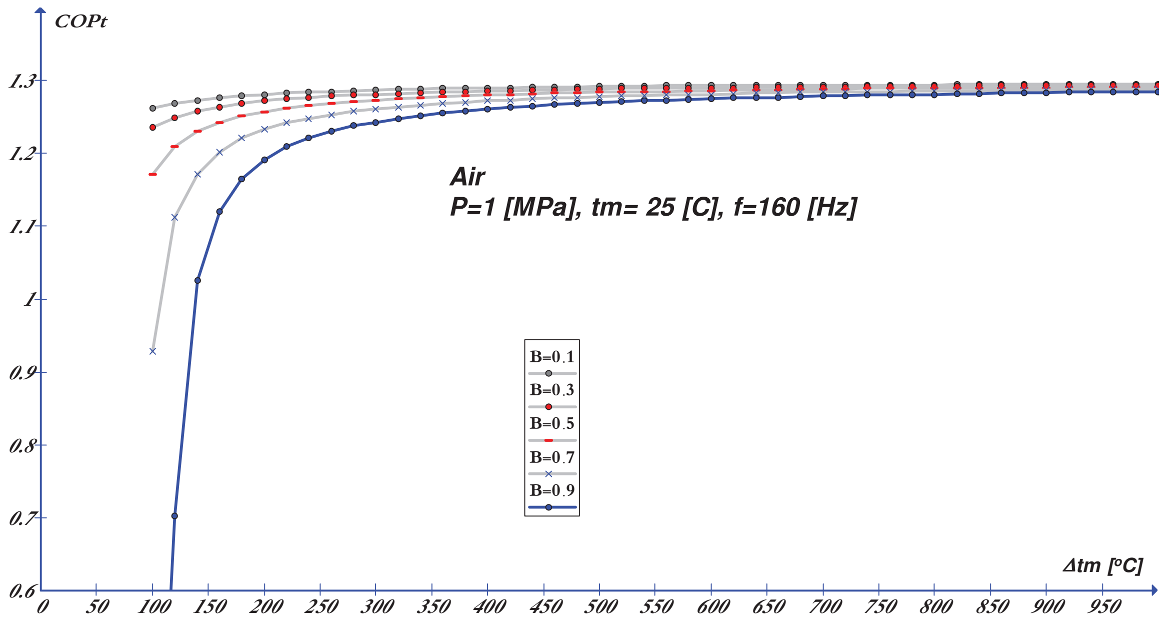

Figure 3: Output for calculated "COPt" as a function of "Δtm" for all range of B when: Gas= Air, and tm=25 [C].

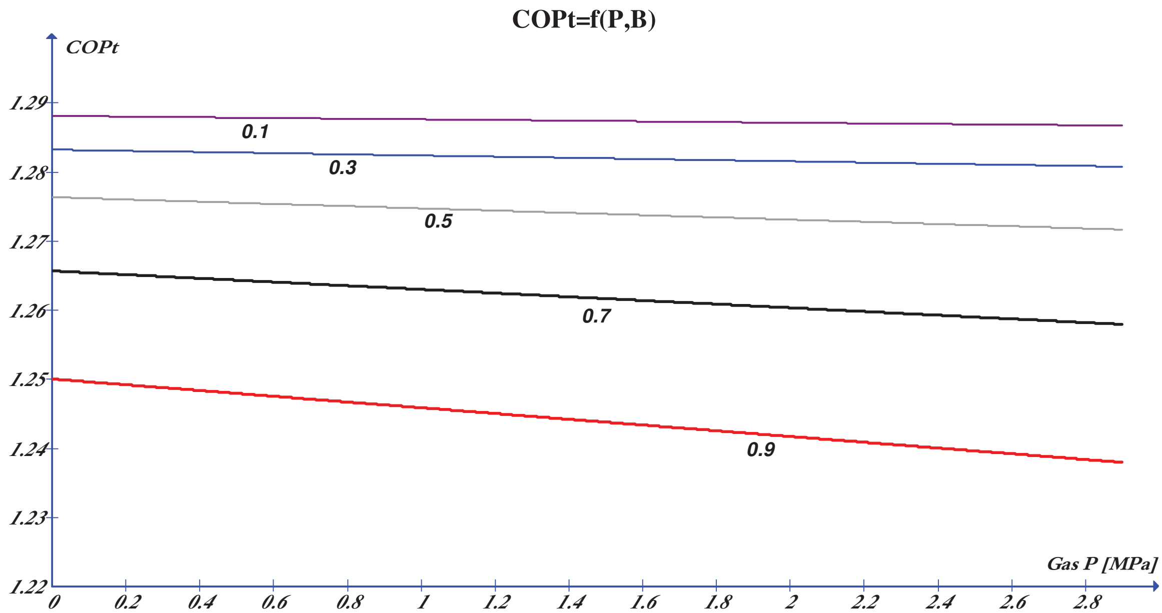

Figure 4: Output for calculated "COPt" as a function of "Pm" for all range of B when: Gas= Air, Δtm=320 [C], and tm=25 [C].

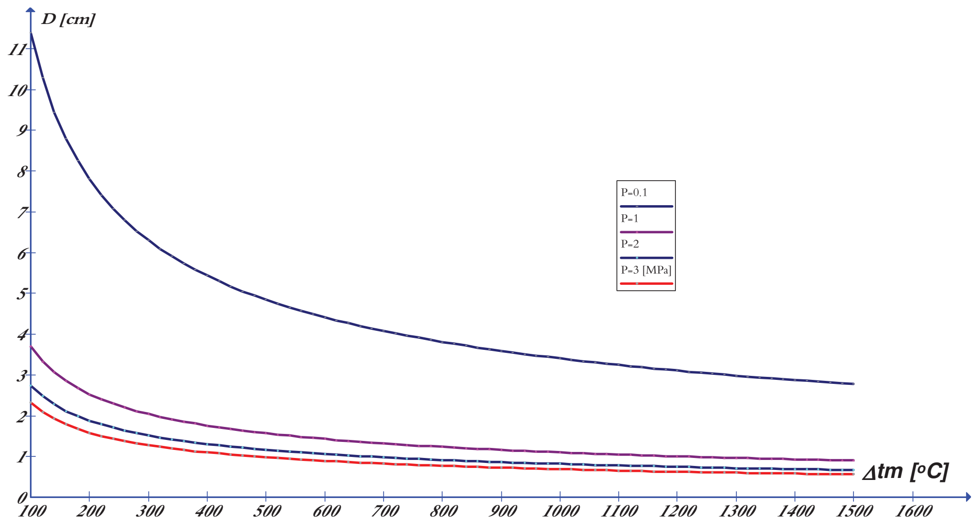

Figure 5: Output for calculated "D [cm]" as a function of "P [MPa]" and "Δtm [C]" for B=0.1 when: Gas= Air, and tm=25 [C].

The "D" approximated relation as a function of "temperature gradient" and "mean pressure" for "B=0.1" would be [9]:

$$D=40.613988*(\Delta tm)^{\wedge}(-0.52081599)*P^{\wedge}(-(0.00080487927*LN(\Delta tm)+0.47364758)) \quad (1)$$

The most important thing in prime mover's is the sound power and resonator diameter. In fig. 5, mean pressure of 10 [bar] may be better for minimizing both diameter and materials thickness. More effect would appear when "Δtm" is lower. Lower "Δtm" is better. Especially when using solar collectors for supplying heat to the prime mover.
Figure (6) and (7) shows impact of "Δtm" and "Qh" on "W/D". Obviously, "W/D" increases potentially with both "Δtm" and "Qh". But, if we take in respect that: increasing "Δtm" causes increased "Γ", which in turn causes decreasing of "COP". A function may describe the all parameter is the function "func=Γ+W/(D.Δtm)". figure (8) shows this function in relation with "Δtm"

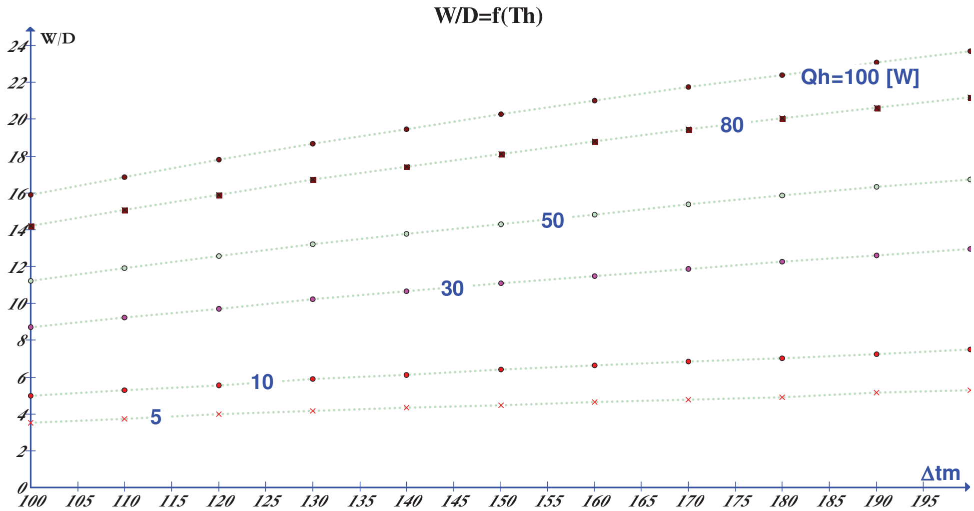

Figure 6: Output for calculated "W/D [W/cm]" as a function of "Δtm [C]" for B=0.1, Pm=10[bar] when: Gas= Air, and tm=25 [C].

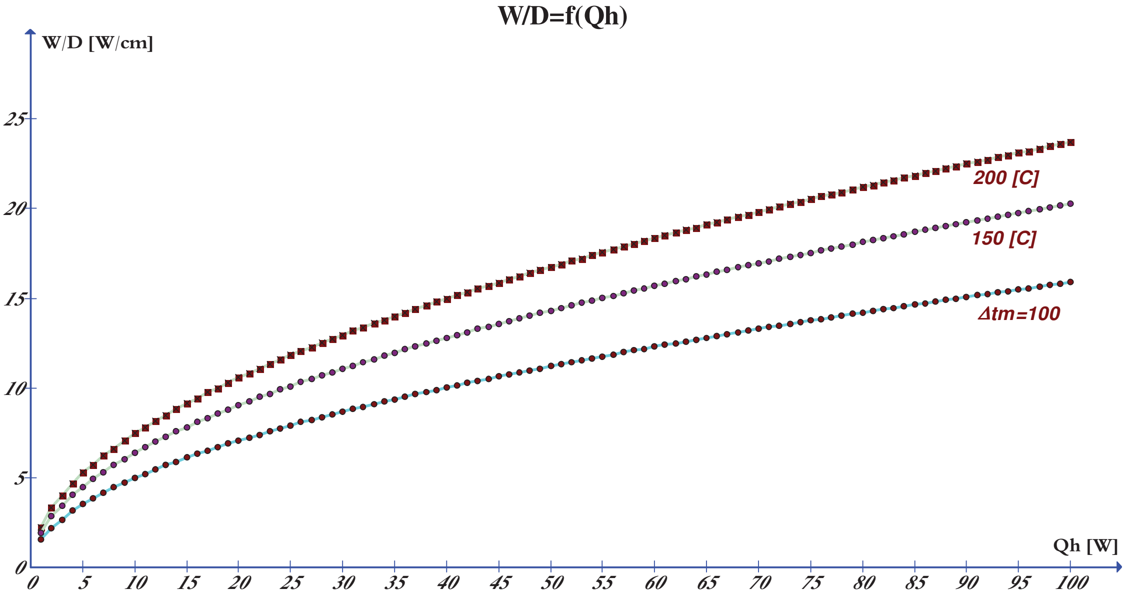

Figure 7: Output for calculated "W/D [W/cm]" as a function of "Qh [W]" for B=0.1, Pm=10[bar] when: Gas= Air, and tm=25 [C].

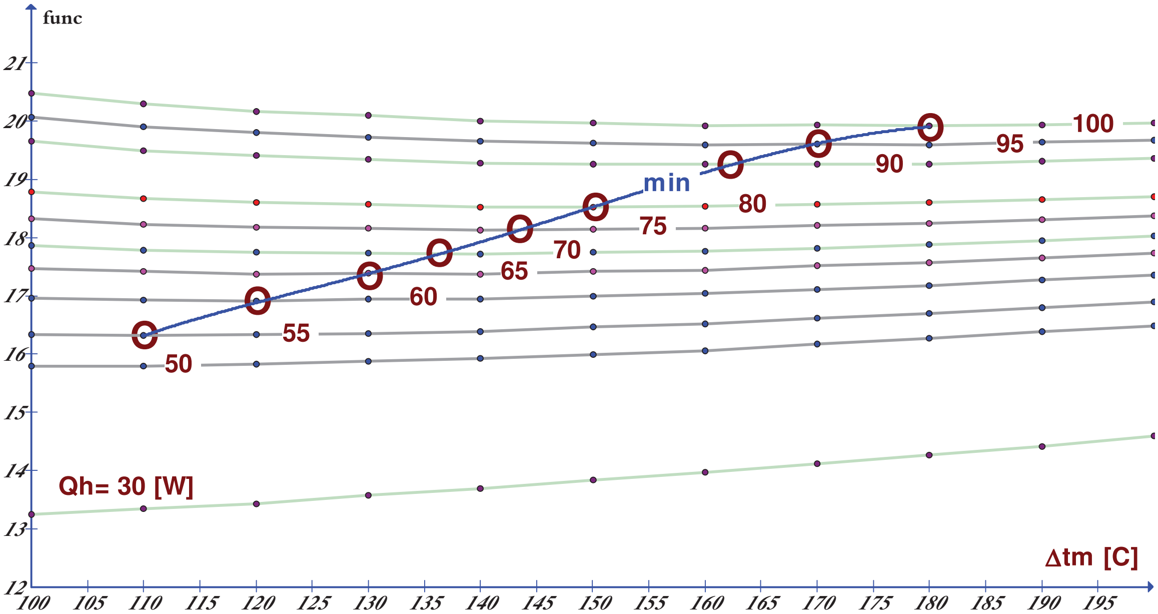

Figure 8: Output for calculated "func" as a function of "Δtm [C]" for B=0.1, Pm=10[bar] when: Gas= Air, and tm=25 [C].

As seen, "func" has minimal "Δtm" for every "Qh". Minimal means optimum parameter. The optimum "Δtm" when designing a prime mover working on "Air" pressurized to 10 [bar] when the low temperature is 25 [C] to produce a wave has Drive ratio "0.03" and frequency 200 [Hz] is 130 [C],when Qh =60 [W].

7. Conclusion

Every blockage ratio has a temperature gradient that affects the operation mode (prime mover – refrigerator). The higher "B" is, the higher "Δtm" is. Similar results are reported in [13] fig (9.6-c).

The desired gas in our case is Air. The mean temperature is 25 [C^o], temperature gradient is: 340 [C^o], and Mean pressure is 0.1 [MPa]. Drive ratio has been chosen to be "D=0.03". It has been founded that Air is good for each prime mover and heat pump. Pm has no impact on the performance of prime mover using "Air" with B>0.7. But it has for prime movers with B<0.7. The lower "B" is, the higher the impact is. It is good to use eq. 1 in evaluating driver diameter. Actually prime movers and refrigerators are useless in case of not pressurized when using air.

To use air in prime movers with low pressure, "Δtm" must be higher and "B" must be lower, so it is less than B=0.1 for prime mover's mode.

An optimum "Δtm" is proportional to the heat to be added. Optimum "Δtm=130 [C]" for the case studied.

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